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LCA OF WASTE MANAGEMENT SYSTEMS

Mixed municipal waste management in the Czech Republic from the point of view of the LCA method

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Abstract
Purpose This paper presents the results of a life-cycle assessment (LCA) study for integrated systems (IS) of mixed municipal waste (MMW) management in the Czech Republic. The seven IS categories assessed were: (a) incineration with slag recovery, (b) incineration without slag recovery, (c) landfills with incineration of the landfill gas by flaring, (d) landfills with recovery of the landfill gas, (e) mechanical–biological treatment (MBT) with aerobic treatment, (f) MBT biodrying with co-incineration of refuse-derived fuel, and (g) MBT biodrying with incineration of refuse-derived fuel from a monosource.
Methods The environmental impacts were evaluated using the CML 2001 methodological approach. The methodology from EDIP 2003 was used for performing the sensitivity analysis on the selection of the methodologies for characterization. The treatment of 1 t of MMW was the functional unit selected. Data was collected from both within the Czech Republic (for incineration plants and landfills), as well as from abroad (for the MBTs). The IS assessed were modelled on the basis of available data and using the best processes and data available from the LCA software.
Results and discussion We established that the integrated system of mixed municipal waste management (IS) of landfills without energy recovery of the landfill gas, as well as the aerobic MBT have the highest environmental impacts. On the other hand, the lowest environmental impacts were found for the MBT biodrying IS. An overall assessment of this IS, both with and without the toxicity and ecotoxicity impact category pollutants and emissions indicators, were compared.
Conclusions A comparison of the environmental impacts of IS landfills to the other IS categories should be made, using both a detailed and long-term inventory. Further, this should also include the closures of the landfill sites, as well as all of the future environmental impacts. It would also be appropriate to include several additional aspects (such as social, technical, and economic factors) for a fully objective assessment and in making the optimal choice of an IS.

Keywords Incineration · Landfilling · Landfills · Life-cycle assessment · Mechanical–biological treatment · Mixed municipal waste

Abbreviations

CML 2001	LCIA characterisation method of Centrum voor Milieukunde Leiden (CML)
EDIP 2003	LCIA characterisation method (Environmental Assessment of Industrial Products)
LCA	Life-cycle assessment
LCIA	Life-cycle impact assessment
IS	Integrated system of mixed municipal waste management
MBT	Mechanical–biological treatment
MBT-Aer	Integrated system MBT, with aerobic treatment

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MBT-Mono	Integrated system MBT biodrying, with incineration of RDF of a monosource
MBT-BD	Integrated system of MBT biodrying, with co-incineration of RDF
MMW	Mixed municipal waste
Land	Integrated system of landfills, with incineration of landfill gas by flaring
Land-R	Integrated system of landfills, with landfill gas recovery
Incin	Integrated system incineration, without ash content recovery
Incin-R	Integrated system incineration, with ash content recovery
20/20	20% release of air emissions and a 20% release of leachate water from the landfill
30/10	30% release of air emissions and a 10% release of leachate water from the landfill

1 Introduction

The most common method of mixed municipal waste (MMW) management currently used in the Czech Republic is that of landfills; in 2006, 75% of municipal waste was placed in a landfill (ISOH 2009). A total of approximately 20% of this municipal waste is recovered; 11–12% for materials and 9% for the recovery of energy. In recent years, there have been many discussions about the possibilities of MBT implementation in the Czech Republic. However, to date, these technologies are still not in operation within the Czech Republic, despite the fact that their implementation has long been considered in some regions. This situation is also complicated and delayed by the fact that the conditions (as well as the necessary legislation) for MBT operation in the Czech Republic have yet to be defined.

This project is instrumental in the assessment of the possible environmental benefits of implementing a specific IS for the management of MMW. With the application of the life-cycle assessment (LCA) methodology, the environmental impacts of each IS could be quantified and assessed and then the different options compared.

There are various tools which are useful for both the inventory and assessment of environmental impacts of waste management systems, as well as in support of the decision-making processes, such as: environmental impact assessments, substance flow analyses, and LCA (Baccini and Brunner 1991; Finnveden and Moberg, 2005a; Grassinger et al. 1998; Kirkeby et al. 2006). LCA assesses both the environmental impacts, as well as the consumption of resources during the entire life cycle of a product; from the extraction of the raw materials, through their production, to their final disposal after last use. A "product" not only describes the product system, but also its services (ISO 14040:2006, ISO 14044:2006). By applying the life-cycle approach to the waste management system, the effects of utilising and disposing of a defined quantity of waste can be assessed without having to look at either the preliminary stages of the product or the service life cycle (Wittmaier et al. 2009).

At first glimpse, it would seem that the use of LCA for the problems of waste management contradicts the purposes and principles of those methods designed to assess the environmental impacts of products "from the cradle to the grave". From this viewpoint, waste management would always be a part of the life cycle of a specific product because they become waste at the end of their useful lifetime. On the other hand, we can view waste management technologies as a service, related to the specific environmental impacts in which we are interested. When viewed from this perspective, two different emission modelling approaches can be put forward: a process approach and a product approach (Bjarnadóttir et al. 2002). The process approach uses ready-made emission and resource consumption factors for the different waste treatment methods, as well as their underlying technological variations. This approach was selected as being crucial for this study.

The concept of the application of LCA to waste management is not new. Several authors have developed mathematical models with which to analyse the management of MMW, i.e. EASEWASTE (Kirkeby et al. 2006), ORWARE (Sonesson et al. 1997), and WASTED (Diaz and Warith 2006). Within these tools, the environmental burdens associated with waste management are included. Weitz et al. (1999) developed an integrated tool to consider both the environmental and economic concerns of different waste management strategies. LCA has also been proposed to support waste management decisions at various different levels because it provides a comprehensive view of both the processes and impacts involved (Finnveden et al. 2007). A very good overview of the uses of LCA in waste management has been described by Cadena et al. (2009). A significant number of publications have explained the use of LCA; using comparisons of different waste management scenarios in order to quantify the environmental burdens and benefits of different proposals (Emery et al. 2007; Finnveden et al. 2005b; Güereca et al. 2006; Wilson 2002). Other authors have studied MSW management systems in different cities or regions using LCA, i.e. Ankara (Özeler et al. 2006), Phuket (Liamsanguan and Gheewala 2008), Gipuzkoa (Muñoz et al. 2004), and Corfu (Skordilis 2004). LCA has also been applied to the study of waste

treatment plants, particularly to anaerobic digestion plants (Ishikawa et al. 2006). Finnveden et al. (2005b) used this tool to test the waste management hierarchy (which gives preference to recycling over either incineration or landfill use), in order to determine those situations in which this hierarchy was not environmentally valid.

The LCA method can be used for the purpose of environmental assessments of alternative waste management systems and/or for the identification of those main areas needing potential improvements, all based upon specific concepts of waste management or the specific technologies involved. The LCA results could be useful in formulating suggestions for the decision-making processes. LCA, within waste management, is primarily focused upon: the identification of environmentally important processes in the waste management chain, the identification of important environmental burdens within these processes, the definitions of the proposed improvement endpoints in local optimizations (the displacement of environmental burdens to other locations), whether or not these are environmentally preferable for the entire waste management system, and lastly, upon the assessment of the environmental impacts of alternative waste management systems throughout their complete life cycle.

One partial goal of the "Concepts of integrated systems for the optimization of mixed municipal waste management preferring the modern principles of EU and their assessment by the LCA method" R&D project was to assess the IS of MMW management, from the environmental point of view. The LCA methodology was chosen for this assessment. The objective was to compare the various integrated systems (not the technologies of landfills, incineration, or MBT), i.e. the composite of both the primary technology (e.g. incineration), as well as the supplementary technology (e.g. landfills). Only the landfill is a terminal method. All of the other technologies have to deal with the outputs that they will generate further on in time. Wastes either go through the system to become a landfill waste product material or it is used in the production of secondary materials and energy generated within the system. The focus of this study was to determine the environmental impacts of different IS within the Czech Republic.

Reflected in this paper is the argument that a perspective of the waste's entire life cycle is a useful tool in order to analyse waste management system processes, since it provides a comparison between the different technologies and the integrated systems of waste management. On the other hand, at present, there are a number of limitations and deficiencies in using LCA software, especially with the database's complexity and with the data (or lack thereof) for the Czech Republic.

2 Methods

2.1 The integrated systems of waste management

Waste management is a complex system for the disposal (or secondary usage) of wastes produced. Currently, waste is not being disposed of at any one facility, but it is usually disposed of in several subsequent facilities. This sequence of technological processes, which participate in the waste management process, is called an integrated system. In this project, the environmental impacts of the following various IS were assessed:

- IS MBT, with aerobic treatment (MBT-Aer)
- IS MBT biodrying, with RDF incineration from a monosource (MBT-Mono)
- IS MBT biodrying, with RDF co-incineration (MBT-BD)
- IS Landfills, with landfill gas incineration by flaring (Land)
- IS Landfills, with recovery of the landfill gas (Land-R)
- IS Incineration, without slag recovery (Incin)
- IS Incineration, with slag recovery (Incin-R)

(The MBT IS, with anaerobic treatment, was not represented within this study because the authors were unable to obtain all of the relevant data necessary for its system modelling within the LCA software.)

2.1.1 MBT (classic) with aerobic treatment, but without use as "compost"

The main technology involved with this IS is the process of mechanical–biological treatment of the MMW (Fig. 1). The outputs of this treatment include: a stabilised organic fraction, a high calorific fraction, and the separation of recyclable metals. The last of the outputs include hazardous materials from the mechanical treatment, inert materials, to wastes from the cleaning of waste gas, all of which then get placed into a landfill. Between 30% and 40% of the waste input mass ends up in the landfill. The high calorific fraction, which is useful as RDF for the co-incineration in the energy industry, represents from 30% to 40% of the waste input mass.

2.1.2 MBT (biodrying) with RDF co-incineration or with RDF incineration from a monosource

The primary technology here is the mechanical–biological treatment of the MMW (Fig. 2a and b). The outputs of this treatment are: RDF, separated recyclable metals, and materials disposed of in landfills (dangerous materials from the mechanical treatment, inert materials, to wastes from the cleaning of waste gas). The materials disposed of at landfills represent from 10% to 20% of the mass waste

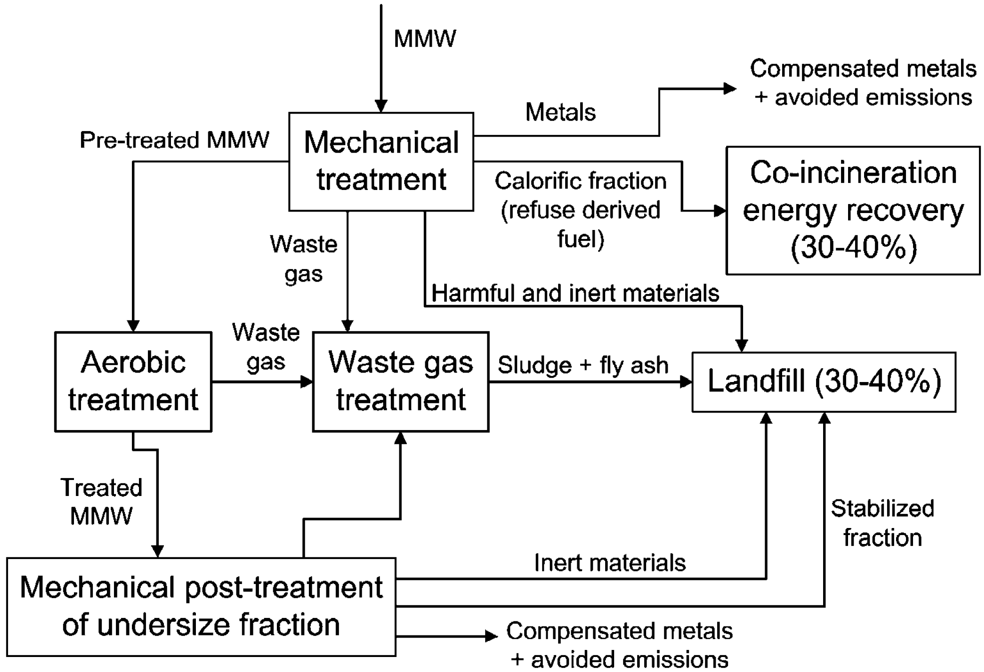


Fig. 1 IS MBT (classic) with aerobic treatment

input. RDF represents from 50% to 60% of the waste input mass and is co-incinerated in the first of these two IS, with energy sources; and in the second of these IS, in a specially installed (monosource) facility, designed for this purpose.

2.1.3 IS landfills with and without energy recovery

In this IS, the main technology involved being that the delivered MMW wastes are spread over the landfill and

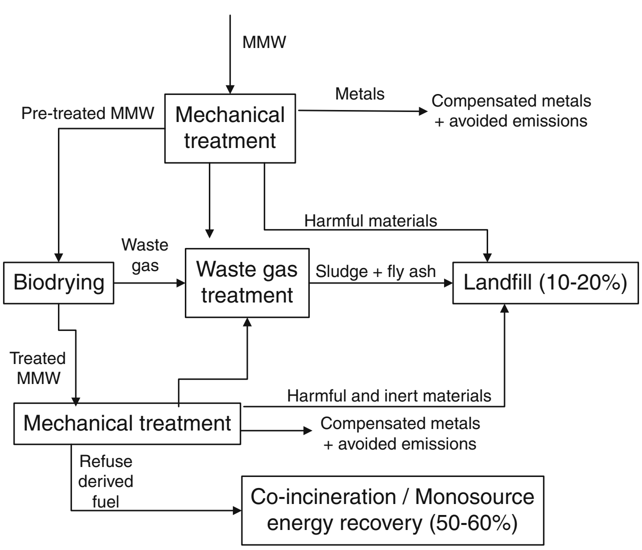


Fig. 2 IS MBT (biodrying) with RDF co-incineration in energy sources and of a monosource. Both of these IS are identical except for the materials used as their means of energy production (co-incineration vs. monosource)

then compacted (Fig. 3a and b). The outputs of this kind of landfill are leachate water and landfill gas. The leachate water runs out through the drainage system into a catchment for this leachate water, which is then used for spraying down the landfill, or is sometimes treated in a wastewater treatment plant. We considered two different cases of the release of various amounts of gases and leachate water into the environment: (a) a 20% release of air emissions, with a 20% release of leachate water from the landfill (Land 20/20 and Land-R 20/20, respectively) and (b) a 30% release of air emissions and a 10% release of leachate water from the landfill (Land 30/10 and Land-R 30/10, respectively, where Land-R stands for a landfill with landfill gas recovery). When IS landfills are performed without the recovery of the landfill gases, the landfill gas is collected and incinerated in a flare tower, without any value having being derived from it. When IS landfills are performed with landfill gas recovery, the landfill gas is collected, and then used for the production of heat and electricity. The heat and electricity produced are then modelled as inverse flows of their production (as the pollution and emissions thus avoided, that would have been produced with the ordinary production of equivalent amounts of heat or electricity). This is the commonly used principle for allocation problem solving (Finnveden 1999).

2.1.4 IS incineration with and without slag recovery

The main technological process of this IS consists the incineration of the waste at a specific facility (a MMW

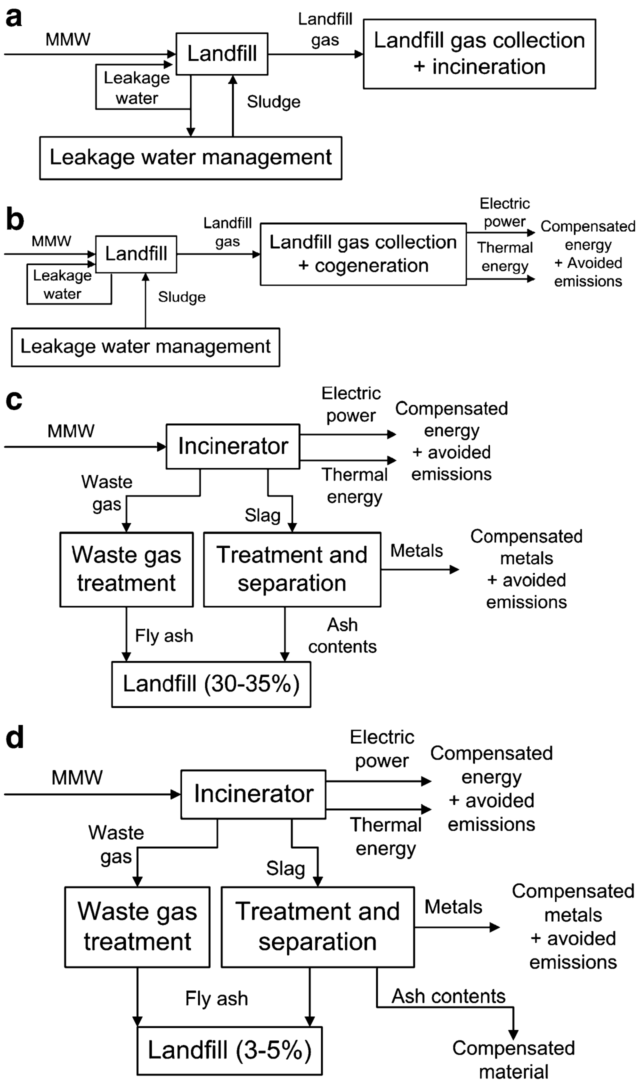


Fig. 3 Flowcharts of the integrated systems of mixed municipal waste management studied: **a** IS landfills with incineration of landfill gas by flaring, **b** IS landfills with landfill gas recovery, **c** IS incineration without slag recovery, and **d** IS incineration with slag recovery

incinerator; Fig. 3c and d). The principle outputs from this technology are heat and electricity, which are then used. The other outputs are metals, slag, waste gas, and fly ash from treatment of the exhaust gas. The slag is treated, and from this process, metals are separated out for subsequent smelting. The waste gas is also treated. In the case of IS incineration without slag recovery, the slag and fly ash produced are put into a landfill (30–35% of the input waste mass). In the case of IS incineration with slag recovery, the slag is treated and the materials are used as construction materials; with these products and processes thus avoiding emissions, and respectively, included in the inventory. In this case, 2–5% of the waste input mass ends up in a landfill.

2.2 LCA methodology

2.2.1 Definition of goal and scope

The aim of this study was to compare the different MMW management IS for conditions within the Czech Republic from an environmental point of view. One tonne of MMW was the functional treatment unit chosen. This functional unit permitted comparison of all of the IS studied, regardless of their treatment capacities.

2.2.2 System boundaries

The choice of a system for the life-cycle approach essentially depends on the depth of the enquiry required. If necessary, not only the operating process, but also all pre- and post-processing involved in the preparation of the materials, as well as in the manufacture of all of the components, building construction, demolition, and disposal of the plant and equipment, and including transport should be taken into account (Wittmaier et al. 2009). This, of course, requires comprehensive data, and the efforts appropriate for their collection. The data often must be verified by making a number of assumptions, which can greatly restrict the general applicability of the results obtained; additionally, they can have significant consequences on the costs of the study itself.

According to previously completed LCA studies on waste treatment plants, in facilities which have been operating for many years, the environmental costs of pre- and post-material processing are of minor importance when compared to the environmental costs of the plant's operation (Wittmaier et al. 2009; Fritsche et al. 2007; Marheineke et al. 2000). In this study, the LCA was principally performed on the management of MMW; including its transportation, production of the necessary materials and energy, consumption of fuel and water, as well as the atmospheric, aquatic, and soil pollution produced.

2.2.3 Inventory analysis and data collection

The methodology used to inventory the problems associated with IS was a questionnaire designed for the plant managers. The data asked and obtained included: the amount of treated MMW; consumption of materials, energy, and water; pollution going into the environment; residues; secondary materials; and energy usage. The data asked in the questionnaire related both to the operational conditions, as well as the economics involved in these processes; additionally, these were occasionally checked and confirmed in situ. Furthermore, the LCA methodology was used to calculate both the environmental interventions

(inventory profile) and the characterisation profiles (results of impact category indicators). The facilities assessed were located both in the Czech Republic (for incinerators and landfills), as well as abroad (the MBTs). Inventory analysis permitted the calculation of different ratios, which corresponded to the resource consumption of the plant, as well as the performance and process yields related to 1 t of MMW. The pollution from diesel consumption to electric production, as well as the relevant processes, was derived by using the GaBi 4 Professional database (PE International). The electricity model covers the consumption of electricity produced in the Czech Republic, including the production and transport from the primary energy sources.

2.2.4 Assumptions

Within the model of IS with landfill, there were two different options of the percentage release of air pollution and leachate water that were analysed. The two options that were considered were with a view to both operational data and published information (Bjarnadóttir et al. 2002; den Boer et al. 2005a). They consisted of: (a) a 20% release of air pollution and a 20% release of leachate water from the landfill and (b) a 30% release of air pollution and a 10% release of leachate from the landfill. The composition of the leachate water was modelled over an average period of 30 years (Bjarnadóttir et al. 2002). For the modelled landfills, the actual averages of landfill water composition were only available for 2–3 years; thus, not very relevant for long-term waste activities within any landfill. Gas emissions from the operation of the transport techniques, used for the mechanical treatment at the landfill, were also included in the landfill model. The gaseous emissions were modelled on the basis of 30 year emission estimate based on real data from Czech landfills, over a 5-year monitoring period (recently the best available data in Czech Republic). The characterisation of air pollutants from the transport techniques of operation processes came from the IWM LCA report (den Boer et al. 2005a). The amount of pollution established was based upon the fuel consumed. Not included were those impacts related to: the amounts of water production necessary for industrial use, impacts related to the production and use of deratization agents, as well as those impacts related to the production of a safety network.

The following assumptions were used in the modelling of IS with incineration. The IWM LCA project data (den Boer et al. 2005a) was used for the inventory; it was then related to the disposal of material outputs from incineration at the landfills (fly ash, slag, and filtrate cake), as well as for the inventory of slag used for construction materials. In the case of incineration with slag recovery, the assumption of a 95% waste mass input was used. In modelling the production of materials from slag, they were used as a substitute for gravel in construction materials.

In the IS with MBT, the assumption was made that the calorific value of RDF obtained from MBT is approximately the same as the calorific value of lignite (approximately 18 MJ/t). The use of RDF in the case of co-incineration is then modelled as a compensation for the lignite production saved. This was included into the model as an inverse flow of lignite production in the Czech Republic. In the case of RDF incineration from a monosource, the electric production from lignite was analysed. The compensation of energy from RDF, by the use of this inverse flow, leads to the avoidance of pollution equal to that which would have come from the production of a corresponding amount of electricity.

2.2.5 Impact characterization

The analysed impact categories were based upon specific characterisation methodologies. The CML methodologies (Heijungs et al. 1992) and the EDIP 2003 (Hauschild and Potting, 2004) were chosen for the calculation of profile characterisations, with particular attention given to CML. CML uses the following impact categories: global warming (GWP100), acidification (AP), photochemical ozone creation potential (POCP), eutrophication (EP), human toxicity potential (HTP), aquatic and terrestrial ecotoxicity potentials (AETP and TETP), as well as ozone layer depletion (ODP). The EDIP 2003 methodology was used for sensitivity analysis, as well as to analyse the influence of the selection method for characterisation and formulation of the significant issues.

3 Results

3.1 Inventory analysis results

The primary inventory data for the selected major elementary flows (considered crucial for the comparison of IS) are summarised in Table 1. Negative values indicate that the given IS saves the usage of some specific input, due to material and/or energy recycling (in some cases this leads to a negative net balance, indicating that the savings of that IS are greater than the raw material inputs).

It is evident that MBT with aerobic treatment is rather dependent upon the consumption of raw material sources, especially crude oil and natural gas. On the other hand, MBT with RDF incineration from a monosource is less demanding on the consumption of hard coal. The highest savings of crude oil were obtained with the incineration with slag recovery IS. Then again, this IS technology is high in water consumption (as IS incineration without slag

Table 1 Selected inventory data of assessed IS (kg/t MMW)

Mass [kg]	MBT-Aer	MBT-Mono	MBÚ-BD	Land 20/20	Land 30/10	Land-R 20/20	Land-R 30/10	Incin	Incin-R
Resources									
Crude oil (resource)	2.43E+00	3.52E+00	8.50E−01	6.55E−01	6.55E−01	6.91E−01	6.91E−01	1.43E+00	7.13E−02
Hard coal (resource)	2.09E+00	−1.23E+01	−1.03E+00	1.31E−01	1.31E−01	−7.36E−01	−7.36E−01	−1.54E+00	−1.60E+00
Lignite (resource)	−2.26E+02	−2.01E+02	−6.43E+02	1.22E+00	1.22E+00	−1.03E+01	−1.03E+01	−4.18E+01	−4.20E+01
Natural gas (resource)	7.92E+00	1.02E+00	8.54E−01	7.00E−02	7.00E−02	−1.73E−01	−1.73E−01	−1.71E+02	−1.71E+02
Water	4.50E+02	3.26E+03	−5.16E+01	2.15E+01	2.15E+01	−1.42E+02	−1.42E+02	3.21E+03	3.20E+03
Emissions into the air									
Ammonia	4.62E−05	1.62E−02	3.80E−03	1.57E−05	1.57E−05	−1.20E−05	−1.20E−05	6.95E−03	6.94E−03
Carbon dioxide	1.09E+02	2.50E+02	−5.43E+01	2.39E+01	3.41E+01	1.15E+01	1.23E+01	4.53E+02	4.48E+02
Carbon monoxide	1.76E−01	7.18E−02	−5.14E−01	4.84E−01	6.47E−01	4.69E−02	4.73E−02	−2.78E−01	−3.01E−01
Nitrogen oxides	1.66E−01	−2.16E−01	−9.45E−02	1.23E−01	1.23E−01	6.02E−02	6.02E−02	2.03E−01	1.39E−01
Sulphur dioxide	4.83E−01	−5.48E+00	−4.97E−01	6.18E−02	6.18E−02	−2.88E−01	−2.88E−01	−1.63E+00	−1.64E+00
Group PAH to air	9.19E−07	3.73E−06	7.69E−08	2.48E−05	2.48E−05	1.55E−07	1.55E−07	−3.05E−06	−3.25E−06
Halogenated organic emissions to air	3.07E−04	1.88E−04	4.09E−05	1.98E−06	1.98E−06	−2.16E−06	−2.16E−06	−8.57E−06	−8.96E−06
Methane	7.57E+00	5.37E+00	7.40E−01	1.24E+01	1.86E+01	8.41E−01	1.27E+00	−1.23E+00	−1.23E+00
Emissions into fresh water									
Adsorbable organic halogen compounds (AOX)	2.21E−02	1.67E−02	3.09E−03	4.47E−05	2.26E−05	2.63E−05	1.33E−05	−1.45E−04	−1.45E−04
Biological oxygen demand (BOD)	8.19E−05	4.41E−05	1.07E−05	2.22E−02	1.11E−02	1.31E−02	6.55E−03	8.16E−04	8.09E−04
Chemical oxygen demand (COD)	5.85E−03	5.29E−02	−1.60E−02	5.88E−02	2.96E−02	3.15E−02	1.42E−02	−2.01E−02	−2.04E−02
Total organic bounded carbon	4.13E−04	3.31E−04	5.38E−05	1.02E−05	1.02E−05	7.68E−06	7.68E−06	−4.32E−04	−1.02E−03
Cadmium (+II)	1.23E−06	3.32E−06	−2.15E−06	8.10E−08	8.10E−08	−5.82E−08	−5.82E−08	6.77E−04	1.85E−04
Chromium (+III)	5.70E−07	−3.64E−06	−1.09E−08	3.09E−08	3.09E−08	−2.04E−07	−2.04E−07	−6.17E−07	−6.27E−07
Chromium (+VI)	2.65E−07	2.42E−07	4.90E−07	3.32E−15	3.32E−15	3.31E−15	3.31E−15	4.01E−04	3.17E−05
Lead (+II)	7.99E−06	−3.33E−05	1.24E−05	3.56E−07	3.56E−07	−2.06E−06	−2.06E−06	2.42E−02	1.33E−03
Mercury (+II)	1.11E−07	1.96E−06	1.73E−07	1.81E−09	1.81E−09	1.07E−09	1.07E−09	7.32E−03	7.32E−03
Nitrate	2.09E−04	3.11E−02	−1.90E−06	2.51E−04	1.34E−04	1.33E−04	6.42E−05	6.03E−04	5.45E−04
Phosphate	2.14E−05	1.87E−05	2.79E−05	6.65E−07	6.65E−07	−7.67E−08	−7.67E−08	4.17E−04	4.15E−04
Emissions into industrial soils									
Cadmium (+II)	2.93E−06	2.21E−06	4.10E−07	2.80E−10	2.80E−10	1.17E−11	1.17E−11	−9.34E−08	−9.35E−08
Chromium (unspecified)	5.92E−05	4.36E−05	8.23E−06	7.68E−08	7.68E−08	8.42E−09	8.42E−09	−2.57E−05	−2.57E−05
Iron	3.33E−04	2.50E−04	4.65E−05	1.12E−07	1.12E−07	1.44E−08	1.44E−08	−3.74E−05	−3.75E−05
Mercury (+II)	1.25E−09	9.23E−10	1.74E−10	1.55E−12	1.55E−12	1.92E−13	1.92E−13	−5.18E−10	−5.18E−10
Ammonia	7.89E−01	5.94E−01	1.10E−01	3.94E−05	3.94E−05	5.65E−06	5.65E−06	−1.34E−02	−1.34E−02
Sulphate	1.85E−02	1.40E−02	2.59E−03	2.63E−03	1.32E−03	1.56E−03	7.78E−04	−4.20E−04	−4.21E−04

recovery is also). Both IS landfill categories are demanding of lignite consumption. It is important to note that the inventory of landfills from a short-term perspective (1 year) is not flawless. Due to the lack of actual long-term operational data from the landfills, as well as data on the closure of landfills, the material to energetic demands assessed for only 1 year of a landfill's operation should be considered minimal values (which in reality may well be higher).

Pollution into the environment for selected elementary flows is presented in Table 1. Just how problematic, from an environmental perspective, the assessment of an IS can be is evident if only the mass pollution flows are considered. For example, while IS incineration delivers higher emissions of metals into waters, they are minor contributors of metal pollution into the soil (as well as being minor contributors of organic pollution into the air). One important finding is that the MBT ISs are relatively energy consumptive. It is necessary to consider the results for MBT as approximate, as the data used for this modelling came from foreign facilities. The results of the impact

category indicators mentioned next are more suitable for the assessment of potential impacts of elementary pollution flows into the environment and for the mutual comparison of different IS.

The inventory results of elementary flows were transferred to the results of the impact category indicators. We found that the rate of environmental interventions in single impact categories showed important degrees of difference. Specifically, the normalisation of the results provides possible comparisons of combined IS.

3.2 Impact assessment results

According to the LCA method, consistent quantifications of environmental impacts were made using impact characterisations (Life-cycle Impact Assessment—LCIA). The importance of this step is that the impacts on the environment of different types of pollution have other different specific impacts; therefore, it is not possible to compare the environmental impacts of systems based solely upon the mass of the emitted pollution.

It is not appropriate to assess the mass of a material (e.g. hydrocarbons) by their differential environmental impacts and then express their pollution by a mass sum. LCIA was based upon the CLM methodology (Heijungs et al. 1992); therefore, the mass flows of pollution into different parts of the environment were converted into impact category indicators.

The inventory data for each IS were classified into different categories based on the characteristics of their impacts and following LCIA's CML methodology (Heijungs et al. 1992). This is represented in Table 2.

The landfills IS, without energy recovery of the landfill gas, has the highest consumption of raw materials (0.023 kg Sb-equiv./1 t of MMW). All of the other assessed IS showed relative savings of raw materials. Both IS incineration and MBT biodrying with RDF co-incineration demonstrated the greatest material savings.

With regards to the acidification category, the most important contributors are both of the landfills IS, where the resulting values of the impact category indicators varied from 0.28 to 6.6 kg SO_2-equiv./1 t of MMW. Additionally, the IS MBT with aerobic treatment has a significant acidification potential, with a value of 0.6 kg SO_2-equiv/ 1 t of MMW. In contrast, IS with incineration has a positive impact on acidification, due to the resulting electric production. This benefit was included in the inverse flow of electric production, using the energy mix specific to the Czech Republic. The savings of materials that cause acidification in IS with incineration are higher than their impacts; therefore, they have a negative balance on acidification (and thus a positive net benefit for the environment).

The eutrophication impact category is mostly caused by IS landfills, with incineration of the landfill gas by flaring (from 3.9 to 5.8 kg PO_4^{3-}-equiv./1 t of MMW). In this impact category, IS MBT with aerobic treatment (0.54 kg PO_4^{3-}-equiv./1 t of MMW), plus IS MBT biodrying with RDF incineration of a monosource (0.37 kg PO_4^{3-}-equiv./ 1 t of MMW), as well as IS landfills with energy recovery (from 0.22 to 0.33 kg PO_4^{3-}-equiv./1 t of MMW) have significant impacts, as well. IS with incineration thus appears to be the most environmentally friendly within the eutrophication category.

The toxicity and ecotoxicity impact categories are mostly dominated by IS with incineration. The low impact of IS with landfills are caused by insufficient data on the long-term effects of the landfills' operations, as well as their influence upon soil quality and water ecosystems. It is usually assumed during a landfill's operation that the

Table 2 Characterization of results

Impact categories	MBT-Aer	MBT-Mono	MBT-BD	Land 20/20	Land 30/10	Land-R 20/20	Land-R 30/10	Incin	Incin-R
Abiotic depletion kg Sb-equiv.	−7.4E−01	−1.1E+00	−2.9E+00	2.3E−02	2.3E−02	−5.3E−02	−5.4E−02	−3.9E+00	−4.0E+00
Acidification kg SO^2-equiv.	6.0E−01	−5.7E+00	−5.6E−01	4.5E+00	6.6E+00	2.8E−01	5.5E−01	−1.5E+00	−1.6E+00
Eutrophication kg phosphate-equiv.	5.4E−01	3.7E−01	6.1E−02	3.9E+00	5.8E+00	2.2E−01	3.3E−01	1.8E−02	9.0E−03
Freshwater ecotoxicity kg DCB-equiv.	7.6E−02	−1.0E−01	7.0E−03	2.1E−02	1.5E−02	−3.4E−03	−7.1E−03	2.7E+01	4.7E+01
Global warming, 100 years kg CO^2-equiv.	3.1E+02	3.9E+02	−3.4E+01	3.3E+02	5.0E+02	3.3E+01	4.4E+01	4.2E+02	4.2E+02
Human toxicity. kg DCB-equiv.	2.9E+00	−1.2E+01	−6.4E−01	1.6E+00	1.8E+00	−7.3E−01	−7.3E−01	1.2E+01	3.9E+02
Ozone layer depletion (steady state) kg R11-equiv.	3.6E−06	−3.2E−05	−2.0E−06	2.6E−07	2.6E−07	−1.7E−06	−1.7E−06	−2.5E−06	−6.2E−06
Photochem. ozone creation kg ethene-equiv.	9.6E−02	−2.2E−01	−3.4E−02	9.7E−02	1.4E−01	−5.9E−03	−3.3E−03	−1.0E−01	−1.2E−01
Terrestrial ecotoxicity kg DCB-equiv.	4.5E−01	5.2E−02	5.2E−02	1.4E−01	7.3E−02	5.1E−02	1.1E−02	6.5E+00	2.6E+01

Impact category indicator results in CML methodology for assessed IS (for 1 t of MMW)

escape of leachate water or toxic substances will not occur after the landfill's closure. However, to the contrary, this is very problematic, and an increase of toxic leachate waters coming from landfills can often be expected over time (Finnveden, 1999). This fact also decreases the calculation for the environmental impacts of IS incineration without slag recovery for use as building products. Slag that is not recovered is disposed of into the landfills after solidification; while the slag used for products has, according to its content of toxic substances, an impact on both toxicity and ecotoxicity. Additionally, IS MBT with aerobic treatment also has significant impacts on toxicity and ecotoxicity.

The IS landfills without energy recovery 30/10 (500 kg CO_2-eqiv./1 t of MMW) has the largest impact on global warming; this category making significant contributions to it due to their contributions of the major landfill gases (CO_2 and CH_4). IS with incineration, as well as IS MBT biodrying with RDF incineration of a monosource, have lower impacts (420 kg CO_2-eqiv. for 1 t of MMW). IS landfills with energy recovery have the lowest impacts upon global warming. IS MBT biodrying with RDF co-generation has a net negative sum.

The impacts of all tested IS in the impact category of ozone layer depletion were relatively low. After performing comparisons of the different IS, the two which had the greatest quantities of pollutants negatively effecting ozone layer depletion come from IS MBT with aerobic treatment (3.6E−06 kg CFC11-equiv./1 t of MMW), as well as from IS landfills without energy recovery (both IS 2.6E−07 kg CFC11-equiv./1 t of MMW). IS landfills without energy recovery (from 9.7E−02 to 1.4E−01 kg C_2H_4-equiv./1 t of MMW), and IS MBT with aerobic treatment (9.6E−02 kg C_2H_4-equiv./1 t of MMW) have the highest impacts within the category of photochemical ozone creation.

The aggregated normalised results of the impact category indicators are presented in Fig. 4. It is evident that the IS MBT with biodrying is the most environmentally sound. The difference between the impacts of IS incineration, both with and without slag recovery, is also very important. This is caused (as discussed above) by the slag's composition, especially the metals contents, which are important to the impact categories of toxicity and ecotoxicity in those cases where they are applied onto the land. Because the results in the human toxicity and ecotoxicity impact category are significantly influenced by local conditions, these impact categories were deleted (the same was true for the Product Category Rules for Environmental Product Declarations). The IS were compared based upon the aggregated normalised results of the impact categories, minus those deleted impact categories.

The reason for excluding the human toxicity and ecotoxicity impact categories was the lack of available information on the basic flows involved within these impact categories. Each facility operator follows their individual local legislative requirements for their monitoring. These requirements do not always reflect the full spectrum of substances emitted; and at the same time, the requirements are not consistent for all facilities. Therefore, a specific emission monitored at one facility is often not monitored at another. Therefore, it is inappropriate to consider these impact categories for the mutual comparisons of IS. Noteworthy from Fig. 5 is that the exclusion of the toxicity and ecotoxicity impact categories leads to a decreased impact of the IS with incineration; while these IS classes are in 2nd and 3rd place for the most environmentally sound of all IS methodologies.

The normalised result sums of the different observed impact category indicators (see Fig. 4) show that IS landfills without energy recovery have the greatest environmental impacts (with and without the inclusion of human toxicity and ecotoxicity (see Fig. 5)). The MBT IS with aerobic treatment also has a relatively high impact. This finding corresponds with a German study (den Boer et al. 2005b), which found that IS incineration was the most environmentally friendly. Similarly, IS landfills were unfavourably assessed in the study by Arena et al. (2003), in which the low environmental efficiency of landfills was established, despite the acceptance of several advantageous

Fig. 4 Normalised values of characterisation results of indicators in the impact categories of LCIA, using the CML 2001 methodology. The normalisation was made for the EU member states 25+3. Normalised results for each category (exc. marine toxicity) were summarised for each IS

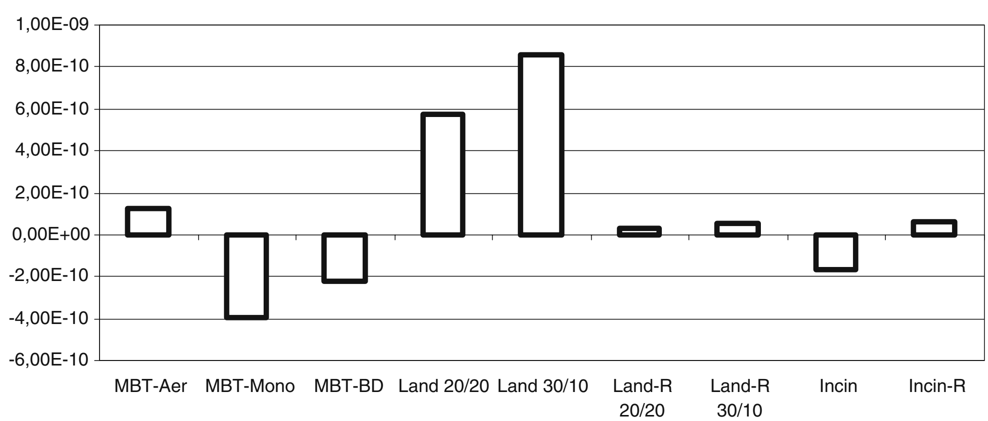
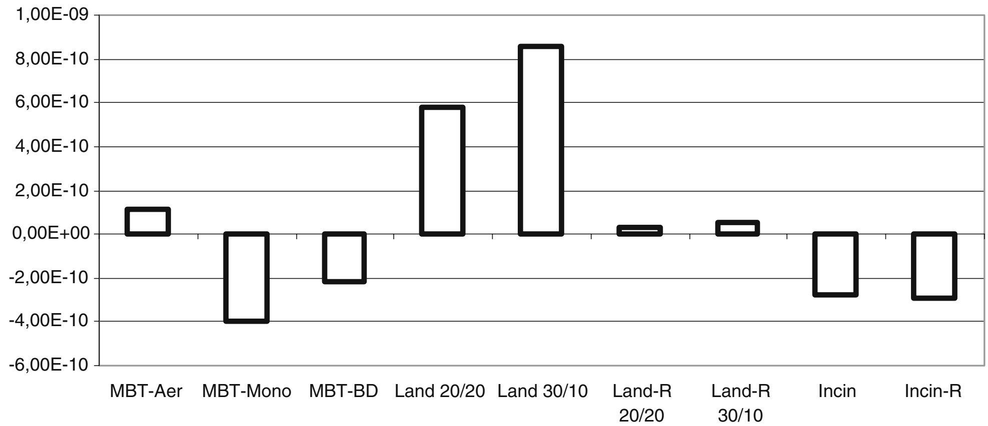


Fig. 5 Normalised values of characterisation results of indicators in the impact category LCIA CML 2001. The normalisation was made for the EU member states 25+3. Normalised results for each category (exc. marine toxicity, freshwater ecotoxicity, human toxicity, and terrestrial ecotoxicity) were summarised for each IS



assumptions. The authors considered that there would have been an even worse overall evaluation of landfills if properties such as odour, visual pollution, and the destruction of natural areas were integrated into the LCA study (Arena et al. 2003).

The main parameter variances in IS life-cycle assessments are: (1) the different assumptions of emission pollution for IS landfills (section 2.2.4), (2) the LCIA methodology used, and (3) the inclusion/exclusion of the toxicity and ecotoxicity impact categories. As to the first point, the differences in the values of the impact category indicators for both options of air pollution and leachate water releases are presented in the tables and figures. Although changes in this assumption lead to relatively significant changes of the environmental impacts (mainly IS landfills without energy recovery), it has no impact on the overall assessment of IS landfills. The sensitivity analysis within the LCIA methodology was based upon a description, using the EDIP 2003 methodology. Table 3 summarises the results of the impact category indicators used in the EDIP 2003 methodology. The aggregated normalised results of these impact category indicators are shown in Fig. 6.

The inclusion/exclusion of the toxicity and ecotoxicity impact category indicators is important in the comparison of IS incineration. In the case of their inclusion, IS incineration with slag recovery is less environmentally friendly than IS incineration without slag recovery. The environmental impact of the solidified landfill slag was omitted in the assessment. The effects of inclusion or exclusion of the impact category toxicity and ecotoxicity (also see the "Discussion" in section 4) was verified by using the EDIP 2003 methodology, which does not reflect these impact categories. The results of the characterization and normalisation in EDIP 2003 showed the same trends as in the CML methodology (with the exclusion of the toxicity and ecotoxicity impact categories (see Fig. 5)). The EDIP 2003 methodology proves that the IS incineration with slag recovery has less-significant environmental impacts than does IS incineration without slag recovery.

4 Discussion

The results obtained confirmed the results from Cadena et al. (2009), that in order to perform the required inventory,

Table 3 Characterization of results

IS	MBT-Aer	MBT-Mono	MBT-BD	Land 20/20	Land 30/10	Land-R 20/20	Land-R 30/10	Incin	Incin-R
Acidification potential m^2 UES	10.4	−104	−9.8	78.7	117	4.5	9.2	−28.4	−29.1
Aquatic eutrophication kg NO^3-equiv.	0.58	0.32	0.04	8.21E−02	0.07	0.04	0.03	0.09	0.06
Global warming kg CO^2-equiv.	310	389	−35.4	335	501	32.6	44.2	420	415
Photochem. ozone formation—human health and materials per s × ppm × hours	0.0002	0.0001	9.56E−06	3.78E−04	0.0006	3.18E−05	4.43E−05	−1.53E−05	−2.52E−05
Photochem. ozone formation—vegetation m^2 UES × ppm × hours	3,102	1,684	89.0	4,729	6,975	414	568	−127	−270
Stratospheric ozone depletion kg R11-equiv.	3.62E−06	−3.19E−05	−1.99E−06	2.61E−07	2.61E−07	−1.70E−06	−1.70E−06	−2.49E−06	−6.23E−06
Terrestrial eutrophication m^2 UES	4.1	−4.0	−1.8	3.1	3.1	1.5	1.5	5.7	4.1

Results of indicators in the impact category LCIA EDIP 2003 for IS)

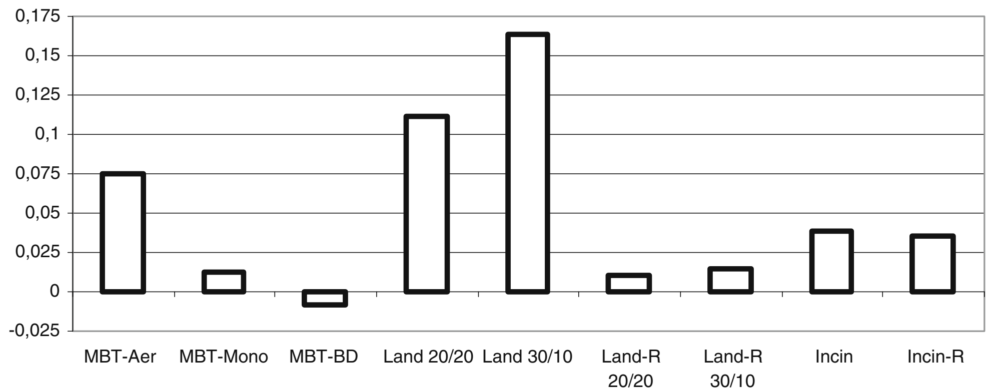


Fig. 6 Normalised values of characterisation results of indicators in the impact category LCIA EDIP 2003. The normalisation was made for the EU member states 25+3 for each IS

LCA in MMW management systems must include wide varieties of the necessary data. In accordance with Barton et al. (1996), some waste management processes were found to be independent of the specific characteristics of the waste processed; while some others were strongly related to these specific characteristics.

It is important to pay attention to both of the major suggestions and limitations of the relevance of the study results. Data collection in the area of waste management is a relatively complicated issue. Data obtained from the operators differs from facility to facility, due to their different applicable legislative regulations. The specific categories of pollution monitored differ at different facilities; significantly decreasing possibilities for parallel comparisons of the environmental interventions at a variety of different facilities.

The second important factor that decreases the possibility of parallel comparisons of IS with landfills, with the other IS, is the above-mentioned factor that the emission balance for any single year of a landfill's operation does not correspond with the real impacts during its entire life cycle (Bjarnadóttir et al. 2002). Using a comparison of the environmental impacts of landfills and incinerators over a short period monitoring of their operation, the landfills are definitely in a better position, as any of their future environmental impacts are thereby not considered. Most of the harmful substances that will leach out into the soil and/or water will do so later on, in case of any damage to the bottom of the landfill. It can be argued that such damage could be repaired; however, such repair will present secondary impacts on the environment, which should then beforehand be included into the equilibrium of the environmental impacts. In this regard, it is important to understand that the results of the environmental impacts for IS landfills are undervalued. In reality, the real impacts undoubtedly would be much greater.

The next limitation on this study's validity is that the facilities assessed only represent an illustrative fraction of all facilities operating in the Czech Republic. The operational data from the MBT facilities were collected from foreign facilities (in Germany and Italy), as this type is not operated within the Czech Republic. The MMW composition is slightly different abroad; therefore, the composition of the pollutants can be quite different. This is not a sufficiently rigorous relative comparison of IS impacts, within the specific impact categories as mentioned in section 3.2. The importance of the rate of a particular impact category's effects is obvious, after a normalisation of the indicator results. The aggregate of the normalised results of the various impact category indicators for all IS was selected by summation in order to simplify the presented results.

Both of the LCIA methodologies used (EDIP and CML) indicated IS landfills without energy recovery, as well as IS MBT with aerobic treatment were the systems having the greatest environmental impacts. Unlike the CML methodology, EDIP 2003 evaluates landfills IS with energy recovery as being more environmentally friendly when compared to IS incineration. MBT biodrying IS with RDF incineration from a monosource, to MBT biodrying IS with co-incineration are the friendliest, according to EDIP 2003; corresponding with the results of CML. The issue discussed in 3.2 relates to the landfill's age and the lack of data on the future environmental consequences of harmful substances in the landfills; and thus not using a long-term perspective. Using the available data, this study assesses the environmental interactions of IS from the perspective of just a single year.

The comparison of landfills IS with energy recovery versus incineration IS is limited, due to the availability of short-time inventory data for the landfills' operations. All future environmental impacts related to a landfill's operation, or to recultivation or other impacts connected to the leachate of harmful substances, were not integrated into the environmental impacts of IS landfills (again due to the inventory data only being available for 1 year operation of the facilities). While the unfriendly impacts of emissions from IS incineration are already included at the time of waste disposal (as well as for landfills IS), it is also necessary to consider their future impacts. Another important aspect is that the release of air pollution and leachate water from the landfill was selected according to studies abroad, whose factors are well-known. If the air pollution

and leachate water releases were in reality higher, then the negative impacts of IS landfills would also be higher. So, the environmental impacts of IS landfills night well be undervalued.

5 Conclusions

It has been established that in the Czech Republic, the highest environmental burden comes from IS landfills without energy recovery, as well as MBT with aerobic treatment. The most environmentally friendly IS are the MBT biodrying with RDF co-incineration IS and MBT biodrying with RDF incineration of a monosource IS. Any comparison of the environmental impacts of IS landfills to the other IS should be made using a detailed long-term inventory, including the closure of the landfills, as well as all of their future environmental impacts. It would also be appropriate to include some additional aspects (such as social, technical, and economic) for a truly objective assessment and in order to make a proper choice of IS.

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